

Health aspects of low-level exposure to RF electromagnetic waves

Occupational or public exposure to RF fields can be properly assessed by taking account of the frequency, modulation, directionality and relative location of the source.

By William G. Scanlon

The exponential growth in recent years in the use of personal communications technologies has renewed interest and concern over the health aspects of exposure to relatively low levels of radio-frequency (RF) radiation (300 kHz to 300 GHz). The interaction between radiating sources and the human body, and the nature and implications of the resulting power absorption, are important issues to analyze when dealing with this issue. Fundamental physical laws and effects help facilitate an informed assessment of exposure scenarios and evaluation of the information reported in both the scientific press and in the mass media.

Basic principles of interaction

At frequencies above RF with extremely short wavelengths, electromagnetic waves (sometimes described in terms of particles in this part of the spectrum) have sufficient photon energy to disrupt atomic bonds in a phenomenon known as ionization. This is how X-rays and other forms of ionizing radiation may damage genetic material in biological cells potentially leading to cancer, birth-defects and other health problems. As frequency is reduced, around the range

of visible light and lower, there is insufficient photon energy (regardless of the wave energy flowing or length of exposure) to produce these disturbances. This radiation is known as non-ionizing. The entire RF portion of the electromagnetic spectrum is therefore classified as non-ionizing with its own distinct properties and mechanisms of interaction.

The description of the interaction between RF waves and living systems discussed here is primarily concerned with the types of exposure encountered with the increasing use of mobile radio and personal communications technology. More thorough descriptions have been presented and revisited many times [1,2,3].

Across the RF spectrum, biological tissue is non-magnetic with permeability, μ (H m^{-1}) (a measure of a material's ability to support a magnetic field) close to that of free-space. Interaction with living systems is therefore a consideration of the influence of an external electric field or, in some circumstances, a magnetically-induced internal electric field. Energy exchanges may occur with both free charges or dipolar (asymmetrically-charged) structures such as water. With an alternating field, free-charges will be accelerated, giving rise to ionic conduction currents and corresponding resistive losses, while dipoles will be reoriented, producing frictional resistance caused by the viscous biological medium. These phenomena both result in risen temperatures in the tissue and account for the well-documented and verified "thermal effect" of exposure to RF [4,5].

These effects vary in magnitude with both frequency of the applied field and tissue type (largely determined by relative water content) and are neatly described by the relative permittivity ϵ_r (dielectric constant) and effective conductivity σ (siemens m^{-1}) of biological tissue at the frequency of interest. From this viewpoint, the human body will interact with an electromagnetic wave as an inhomogeneous, lossy dielectric structure. The wave will propagate in the material with reduced speed, depending on the dielectric constant, leading to a reduction in its wavelength

$$\lambda_m = \frac{\lambda_o}{\sqrt{\epsilon_r}}$$

where λ_o is the wavelength in free-space and λ_m is the wavelength in a material of dielectric constant ϵ_r .

RF radiation will couple into a living organism and produce both absorption and biological-induction effects. The most simple model for this coupling is a layered lossy-dielectric semi-infinite slab (Figure 1). Here, a plane wave is normally incident on several layers of body tissue, e.g., skin, fat and muscle. As the wave passes through the air-skin interface, a small amount of power is reflected back towards the source and the remainder propagates through the skin layer and is attenuated as it progresses. It is common to represent this attenuation for a given medium in terms of penetration depth, δ in m

$$\delta = \frac{1}{\omega \left[\frac{\mu \epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right) \right]^{1/2}}$$

where ω is the angular frequency of the wave (rad s^{-1}) and ϵ is the permittivity of the medium (F m^{-1}). An alternative name for δ is "skin-depth," which is avoided here considering the obvious risk of confusion. The penetration depth is therefore dependent on frequency and tissue parameters (themselves frequency dependent), and represents the distance a wave must travel in the dielectric before it is attenuated to e^{-1} or 36.7% of the field strength at the surface (or 13.5% of the original power density). Table 1 shows the penetration depth of waves of increasing frequency in typical body tissues, the material parameters for each frequency were determined using the Federal Communications Commission (FCC) web utility for calculating tissue dielectric properties (www.fcc.gov/fcc-bin/dielec.sh).

As the wave encounters the skin-fat interface, a further reflection back into the skin layer occurs, and the remainder propagates onward. It is clear that the penetration depth is key to determining the field (or power density) levels within such a tissue model and can directly deduce that as fre-

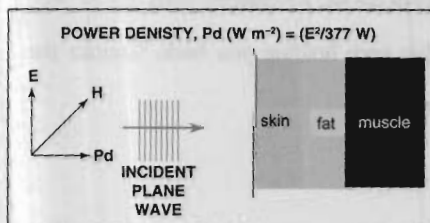


Figure 1. Infinite half-space layered tissue model.

Frequency (MHz)	Blood	Muscle	Brain	Fat
	Depth of penetration (mm)			
150	34.9	43.2	49.6	176
915	9.0	9.7	10.7	34.5
2,450	3.5	3.7	4.2	13.2
5,800	1.6	1.6	1.8	5.8

Table 1. Depth of penetration in biological tissues as a function of frequency.

quency is increased, penetration into the body is reduced. However, this model has some important limitations in the assessment of exposure to RF fields; human bodies are both geometrically and electromagnetically complex. Tissues are not structured in well-defined layers and the model considers only plane-wave (far-field) irradiation.

Questions may also arise as to the possibility of areas of field focusing or the creation of standing waves and, as early school physics reminds us, obliquely incident waves entering a medium with a different speed of propagation will suffer from refraction. Modern numerical modeling techniques such as the finite-difference time-do-



Figure 2. Example 3D tissue model used for numerical modeling of RF exposure scenarios (adult male torso [11], with cut-away for illustration).

main (FDTD) technique [6] allow the direct calculation of fields within three-dimensional complex structures such as the human body (Figure 2). FDTD is highly flexible and may be used to determine the electromagnetic interactions with plane-wave (far-field) and close-coupled (near-field) sources [7,8,9].

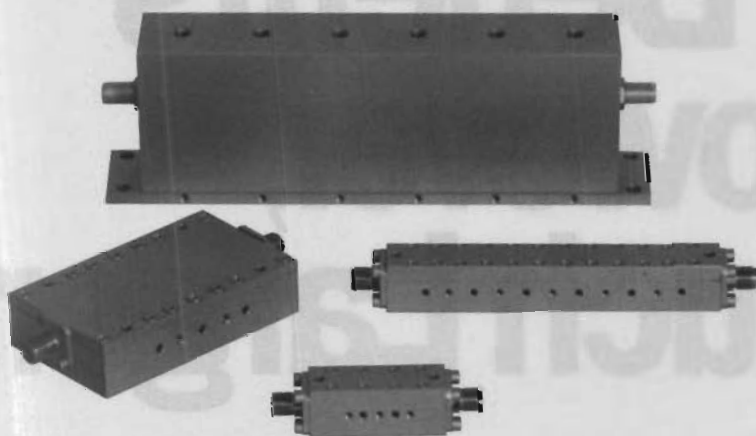
Exposure guidelines

Exposure guidelines exist to protect both occupational users and the general public from long- or short-term health hazards associated with RF radiation sources. For example, in the United Kingdom, the National Radiological Protection Board (NRPB) is responsible for setting and reviewing exposure standards, based on current and past peer-reviewed scientific evidence and the international guidance provided by the European Union, the International Commission on Non-ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO) [10].

Currently, both international and national exposure limits are based on the thermal effects of electromagnetic irradiation and for RF frequencies are specified in terms of specific absorption rate (SAR; $W\ kg^{-1}$). This derived parameter was chosen as it represents the energy dissipated per unit time per unit mass and takes into account the type of source, frequency of operation and duration of exposure. It has been shown repeatedly that known biological effects are proportional to this rate of energy deposition. SAR limits are divided into whole-body average and peak values; this reflects the complicated nature of bioelectromagnetic in-

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teractions. The assessment of SAR from field levels and exposure conditions is complicated and is the subject of significant ongoing research. For far-field exposures, there is both experimental and theoretical evidence leading to a consensus about the incident power density (P_d , $W m^{-2}$) required to create limiting levels of peak and average

SAR [12]. For near-field exposures such as mobile telephone handsets, the concept of power density is inappropriate and the investigator must take account of the location of the source antenna, the antenna characteristics and the detailed dielectric structure of the human body. This more thorough approach ensures that effects such as standing

waves, focusing of electromagnetic fields and the nature of the electrostatic and induction fields are considered.

The current international occupational limit for whole-body average SAR is $0.4 W kg^{-1}$ [13]. This is based on the assumption that $4 W kg^{-1}$ may effect a $1^\circ C$ rise in body tissue temperature (safety factor of 10); above this level the thermoregulatory systems within the body become stressed and eventually are overcome, potentially leading to tissue damage. For members of the public who may be unaware of their exposure, a further factor of 5 is introduced leading to a limit of $0.08 W kg^{-1}$, i.e., 2% of the threshold level for thermal effects.

Detailed information on both peak and whole-body average SAR may be calculated from knowledge of the electric field distribution within the body (either by way of measurements within tissue substitutes or numerical simulation). The relationship takes account of energy losses by including the electrical conductivity, σ ($S m^{-1}$) of the tissue

$$SAR = \frac{\sigma E^2}{\rho} (W kg^{-1})$$

where E is the electric field strength ($V m^{-1}$) and ρ is the tissue mass density ($kg m^{-3}$).

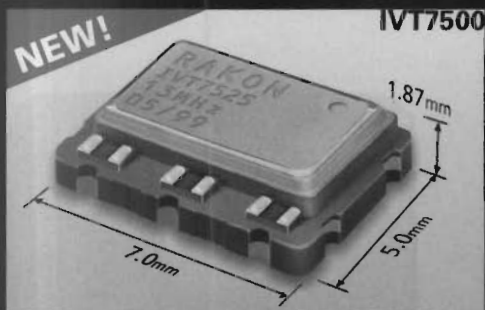
Near-field interaction

In close proximity to RF sources, the electromagnetic field may be divided into three broad classifications: electrostatic, induction and radiating. The electrostatic and induction field components have a large magnitude close to the source but fall off rapidly with distance. These fields do not radiate but store energy in the space surrounding the source. In contrast, the radiation field falls off linearly with distance (leading to the inverse-square power law) and is the combination of an electric and magnetic field in phase (when the electric field is at a maximum, the magnetic field is also) but spatially at right angles to each other in a plane perpendicular to the direction of propagation.

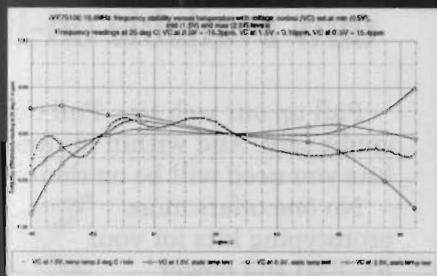
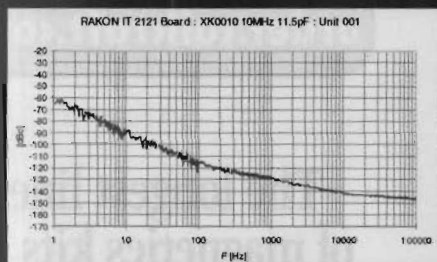
The near-field can be defined as the area surrounding a source where the electrostatic and inductive (reactive) field components dominate. For practical assessments, the boundary of the near-field is difficult to determine as its extent may be enlarged because of the presence of metallic and dielectric objects (such as the human body). This is important, however, as knowledge of near-field components is essential for exposure assessment, yet their amplitude can be as much as an order of magnitude or more than expected, depending on the nature of the coupling.

The most prevalent near-field exposures

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at RF occurs when using personal communications devices such as cellular telephones, domestic cordless telephones and other systems used by industry, the emergency services and security forces. Short-range devices, such as cordless handsets, operate at power levels much less than 100 mW; however, security and other personal

transmitters may operate as high as 10 W. Current public concern is with mobile (cellular) telephones, particularly digital variants (at 900 MHz and 1,800/1,900 MHz). In this case, the transmitter power is variable (as high as 1 W) and may depend on the transmission characteristics between the base station and the phone. Recent studies

have shown that these phones can operate close to the exposure limits when held close to the head [14,15], and more research is required. Within the head of the user, near-field exposure will lead to a localized pattern of absorption dependent on operating frequency, handset design and geometry and composition of the head. This has led to concern about the absorption levels in the brains of children exposed during mobile phone operation. A child's head is not just smaller, but has reduced shielding between the brain and mobile antenna. However, numerical analysis of near-field exposure using anatomically realistic head models has shown that there is no significant difference between adults and children [16].

Figure 3 shows how numerical modeling (this example using commercially available software: XFDTD from Remcom) may be used to determine the electric field distribution within and surrounding a body under near-field exposure. Therefore, the SAR within small elements of tissue can be readily determined. In the example shown, the transmitter (the outline of the case is identified) is mounted close to the chest with a 2.45 GHz source fed into a short monopole antenna. A full 3D model of the transmitter and body was used; a single "slice" is shown, horizontally through the upper chest area where each square represents a cube of dimension 5 mm. At this frequency, the penetration into the body is slight, within a few centimeters the fields are reduced by more than 18 dB, corresponding to a power reduction of 1.6% of the maximum field surrounding the antenna. The deep chest areas (including lungs and heart) experience relative fields lower than -72 dB ($6.3 \times 10^{-6}\%$); this effectively means that at these higher frequencies, the outer tissues dissipate the incident electromagnetic fields rapidly and internal body structures are naturally protected.

Far-field interaction

Moving further away from an RF source, the electrostatic and induction fields fall off rapidly with distance and the radiating field (i.e., where the electric and magnetic fields have a $1/r$ dependence) dominates. The distance at which this occurs depends on the effective aperture of the source antenna and the operating wavelength; at this point the spherical wave-front begins to approximate a plane, uniform phase wave-front to a remote observer. Public far-field exposure occurs with sources such as television and broadcast radio transmitters, cellular base stations and emergency services transmitters.

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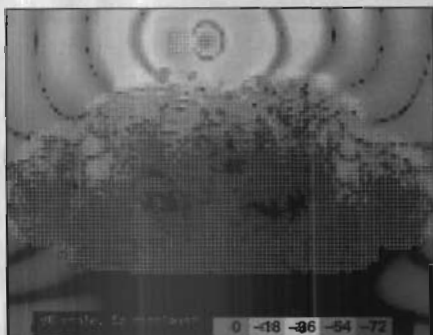


Figure 3. FDTD calculated electric field surrounding and within the chest of an adult male under exposure from a 2.45 GHz transmitter close to the chest. Axial slice, through feed-point of the antenna.

ductive coupling to the source does not occur, i.e., assume that perturbations in the radiated field have a negligible effect on the source itself, equivalent to considering radiation from a source at infinite distance. The electromagnetic wave is effectively incident uniformly from head-to-toe with a particular power density. The body tissues will absorb some and reflect some of this power, de-

pending on the type of tissue and the frequency of the wave. Resonant absorption will also occur when as the height of the body approaches a half or a quarter of a wavelength. Calculated resonant frequencies [17] (when maximum absorption, i.e., whole-body average SAR, will occur) for different body heights are shown in Table 2.

As shown in Table 2, under far-field exposure the resonant frequencies of both adults and children are more likely to occur within the VHF (30–300 MHz) band that includes broadcast radio and other public services. Penetration into the body is also increased at such frequencies. Table 3 compares the penetration into a semi-infinite slab of muscle at broadcast radio and cellular telephone frequencies. At 100 MHz the wave is not absorbed much in the outer layers and will penetrate deep into the body. At 900 MHz and 1,800 MHz, this is not the case and the power will tend to be absorbed in the outer layers of skin, fat and, to a lesser degree, muscle.

Unlike the near-field exposure condition, Table 3 illustrates how an 1,800 MHz cellular telephone signal is less penetrative

(and therefore less likely to introduce serious disturbance) than a 900 MHz signal. The inference is that at lower frequency fields will be more penetrative, producing higher levels of internal fields within the brain and other organs associated with serious threat of disease. Considering that whole-body resonance occurs at frequencies around 100 MHz, it appears that cellular base stations (which operate at extremely low levels of output power) present much lower exposures than broadcast or other service transmitters.

Assessment of far-field exposure levels requires calculation or measurement of the field-strength or power density at the point of reference. The limiting SAR for public exposure is then related to a power density, depending on frequency [13]; for the range 400 MHz to 2 GHz, the power density limit in (mW cm^{-2}) is $f^2/2,000$, where f is the operational frequency in MHz. Therefore for 900 MHz, the limit is 0.45 mW cm^{-2} and 0.9 mW cm^{-2} for 1,800 MHz.

Thermal effects

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Description	Height (m)	isolated f_{res} (MHz)	grounded f_{res} (MHz)
Adult	1.76	65	35
10 years	1.38	80	55
5 years	1.1	105	70
1 year	0.75	150	100

Table 2. Calculated resonant frequency for both grounded and isolated in air conditions, based on whole-body average SAR [17].

human body tissue may cause a rise in temperature that is related to the frequency of the wave and the nature of the tissue. This (thermal) effect is well known, understood and universally accepted.

Elevations of tissue temperature may invoke various physiological and thermoregulatory responses within the individual. These include decreased ability to perform mental or physical tasks as body temperature increases. Similar effects have been reported in individual subjects to other forms of heat stress such as prolonged work in hot environments. At high levels of exposure ($> 100 \text{ W kg}^{-1}$), thermal loading becomes excessive and both direct cellular damage (such as cataract formation) or indirect thermoregulatory effects

may occur, depending on the nature of the rise. Cell biochemistry may also be affected by high temperature, and must be considered when evaluating reports of "effects at power levels lower than the thermal limit" to ensure that the RF exposure is well quantified and understood, especially when considering near-field scenarios.

However, it is extremely unlikely that the SAR levels needed to produce such high exposure effects would be experienced by individuals close to telecommunications or other radio equipment including mobile telephones. In evaluating research, however, the possibility of a thermal effect (by localized heating or otherwise) must be ruled out before deeming an effect as non-thermal; this is particularly important for near-field

or semi-near-field exposures where the magnitude of the reactive field components may be unknown.

Non-thermal effects

All non-ionizing radiation including RF has insufficient proton energy to disrupt chemical bonds or modify DNA. This leads to the conclusion that non-ionizing radiation cannot directly cause genetic disorders or cancer. A broad range of negative health effects have been anecdotally linked to exposure to non-thermal levels of radiowave exposure, some have even been demonstrated in isolated research studies [18]. The constantly-expanding list includes: headaches, sleeplessness, poor academic performance, leukemia, lymphoma, brain tumors, DNA

Frequency (MHz)	Penetration depth (mm)	Pd at 1 cm	Pd at 10 cm
100	49.0	67%	2%
950	9.4	13%	$6 \times 10^{-6}\%$
1,800	5.2	2%	$4 \times 10^{-16}\%$

Table 3. Calculated power levels (relative to the incident power density) in a semi-infinite muscle slab model.



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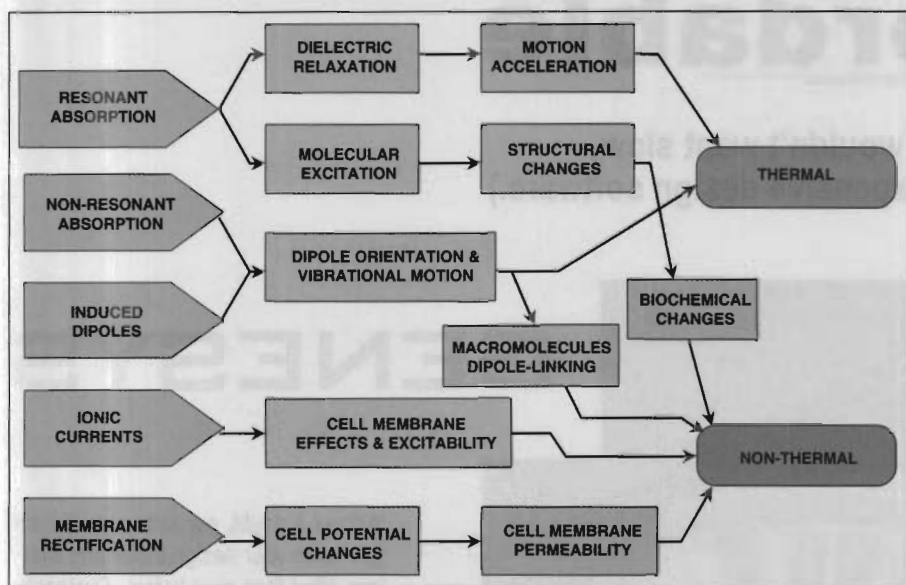


Figure 4. Possible mechanisms for the development of health effects because of RF exposure.

splitting, miscarriage, skin cancer, breast cancer, lung cancer, altered EEG, altered reaction times and low birth weight. It would

be impossible to comment on all the postulated non-thermal effects. It is important to be aware of some potential mechanisms for

non-thermal and thermal effects caused by RF exposure.

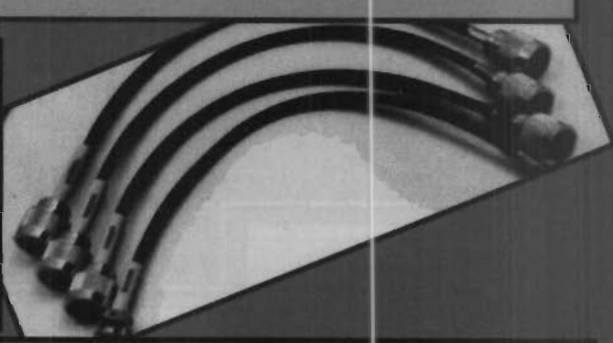
Figure 4 describes some of the possible pathways for thermal and non-thermal effects. Electromagnetic power absorption occurs when some of the wave energy from the incident field is converted to kinetic energy within the biological system. Within biological media and at specific frequencies, resonant absorption effects occur (do not confuse with the whole-body resonance discussed earlier); molecules with dimensions approaching the wavelength within the medium may undergo structural changes, although this is more likely to occur at frequencies greater than 10 GHz. Another resonant process is dielectric relaxation, where the time taken for a molecule to realign itself approaches the reciprocal of the frequency of excitation; this leads to accelerated motion that is damped by biological fluids and produces heating. The main absorption effect, however, is the vibrational motion of dipolar molecules such as water. Here the resulting effect is thermal (kinetic), but some researchers have suggested that this may introduce unnatural dipole linking



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or the formation of pseudo macromolecules that induce various non-thermal effects. Although plausible, this mechanism is highly unlikely as biochemical reactions are relatively slow compared with the rate of change of the imposing field.

Molecular induction effects are also considered in Figure 4. High potentials (high

field-strengths) may induce the formation of polarized molecules (dipoles) that are then subject to the absorption effects mentioned previously. Additionally, naturally occurring ions will tend to move creating current flow that may possibly effect cell membranes; again the rapid reversal of the applied field at high frequencies will tend to negate these

effects. Biological material can be non-linear and therefore produce rectification effects that may affect cell potentials and therefore cell membrane permeability (not magnetic permeability), possibly interfering with the correct functioning of the cell.

The use of time-division access schemes on digital mobile telephony systems has renewed interest in the effects of pulsed fields. Contrary to recent reports, pulsed fields have been investigated for more than 40 years [19] without conclusive evidence of negative health effects. Although experiments have also been reported that conclude that pulsed fields at VHF may improve life expectancy in mice [20]. Before the recent emergence of digital mobile telephones, concern was with pulsed radar systems (typically 500 cycles per second or around twice the rate of a global system for mobile communications (GSM) telephone, 217 Hz). Postow & Swicord [21] reviewed more than 26 studies comparing radar-type exposure with continuous wave irradiation. They concluded that there was no compelling evidence at that time or clear pattern of results, except when considering power levels strong enough to induce thermoelastic expansion (a thermal effect) of biological structures that are not normally encountered by the general public.

There has also been concern about the blood-brain barrier that maintains an exclusive cerebral environment by the selective passage of substances from the blood stream. Early work concluded that if sufficient heating occurred with RF exposure then the functionality of this barrier could be affected. More recently, additional studies [22] have reported increased barrier permeability at SAR levels as low as 0.016 W kg^{-1} . The implications of these unreplicated findings is currently unknown; most public far-field exposure levels do not approach this level of SAR but near-field exposure such as mobile telephones may be of concern.

Animal studies have also been used to determine the existence and possible characteristics of non-thermal health effects. A recent Australian study involving genetically engineered mice [23] has received extensive publicity. Increased rates of lymphoma incidence were found in an exposed group of mice over the rate for the control group. The mice had been genetically engineered to be prone to lymphoma and one group was exposed to 900 MHz pulsed radiation. However, before this work can be used as the basis of health protection decisions, it must be established that exposure to RF can

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also induce lymphomas in normal, non-genetically modified mice. In addition, because they were unrestrained the exposure conditions for the mice were variable, and it cannot be determined what level is required for induction of lymphoma in these mice. If these results can be reliably replicated, it will be critical to determine the dose-response relationship for lymphoma induction, and to determine whether the effect occurs for other tumors and in other species. It should also be noted that at this frequency, the radiation will fully penetrate the mouse and the experiment was designed in such a way that wave reflections may increase the exposure beyond thermal limits for mice. Other experiments with pulsed waves have been performed on mice or rats with negative results [24,25]; such "negative" studies seldom receive the level of media exposure associated with highly sensational "unquestionable health-risk" material.

The issue of risk

Before concluding, it would be appropriate

to consider the issue of risk and the management of the perception of risk. The WHO International EMF project status report suggests that the general public is overestimating the risks from electromagnetic exposure:

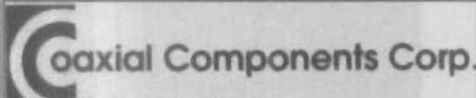
"People with little or no understanding of the health risks of electromagnetic fields view them as an unknown hazard, so they perceive them at a much higher level of risk than those with which they are familiar. Provision and communication of easily understood information on the nature of the health risks from exposure to these fields, placing them in perspective with other risks, and an explanation of how risks are determined, will assist in alleviating people's concerns." [26]

Research is continuing but the scientific principle holds that a negative relationship cannot be proved. The WHO recommends research into brain and other cancers of the head (to reassure the users of mobile telephones), leukemia and lymphoma. Additionally, they are calling for research into "other health effects" including reports of headaches, dizziness,

etc. as it appears that those affected cannot tell if a transmitter is on or off in laboratory testing. This suggests that psychological factors may be involved.

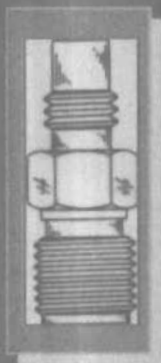
For near-field exposures, there is an important requirement to determine the peak and whole-body average SAR for representative situations. This can be performed experimentally at significant cost or may be determined using established and verified numerical modeling, such as FDTD. At SAR levels below the current limits, there is no conclusive evidence of either short-term or long-term health hazards. The proliferation of mobile telephones is a good reason for continuing research in this field, although it may be a decade or more before any substantial conclusions are reached.

Concerning far-field exposures, simple calculations can quickly determine the power density incident on individuals, although consideration of multipath and other effects may be required in some cases. It would appear that the exposure from commonly occurring transmitters such as mobile telephone base stations and broadcast transmitters is at levels several orders of

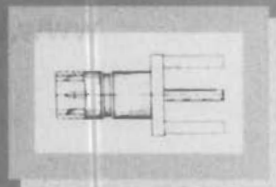


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